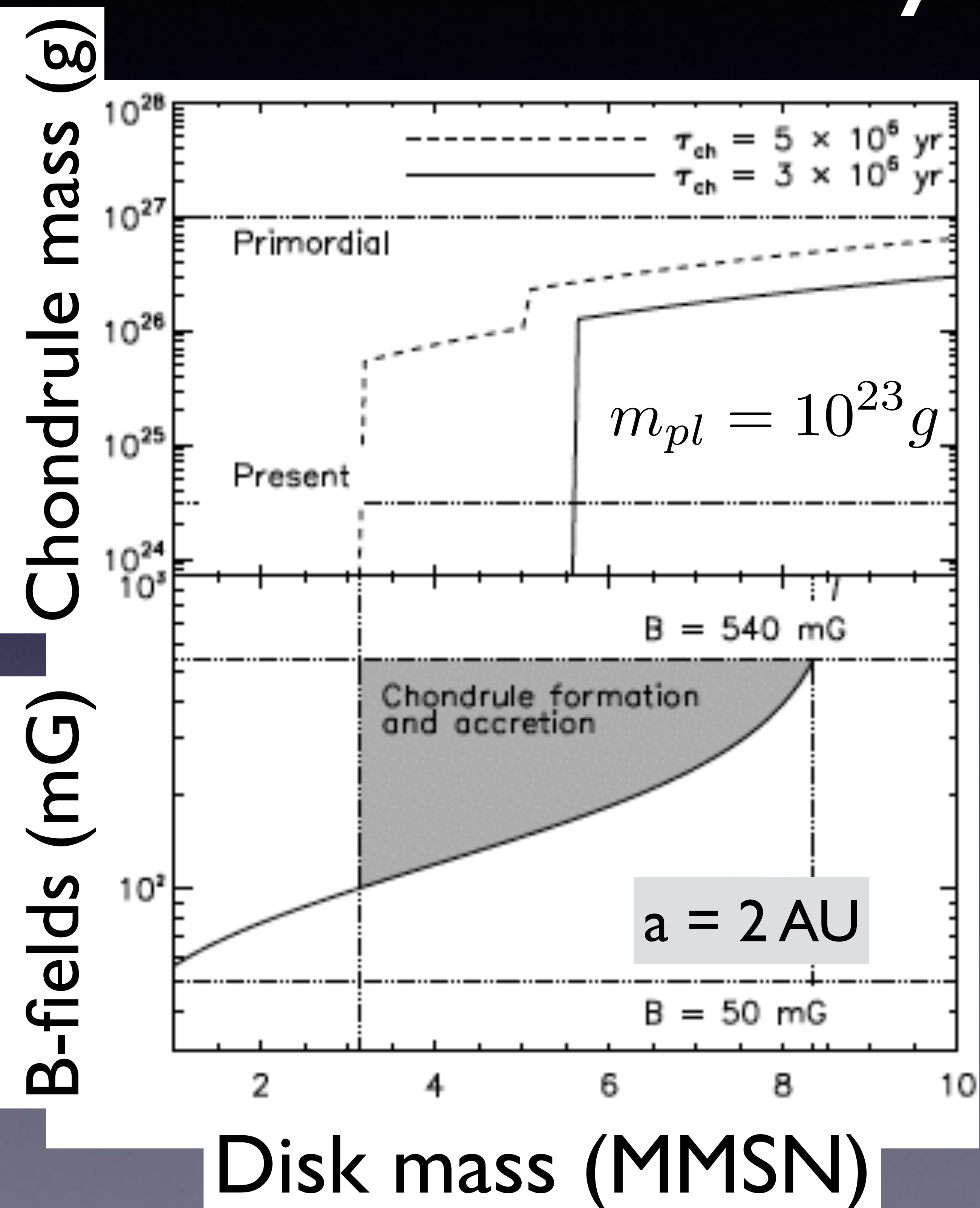
Impact Jetting and the Origin of Ordinary Chondrites



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JPL: Neal Turner, Joseph Masiero

CfCA/NAOJ: Shigeru Wakita, Yuji Matsumoto, Shoichi Oshino

Chondrules: the primitive material formed in the Solar Nebula (disk)

abundant in chondrites
(up to 80 % by volume)

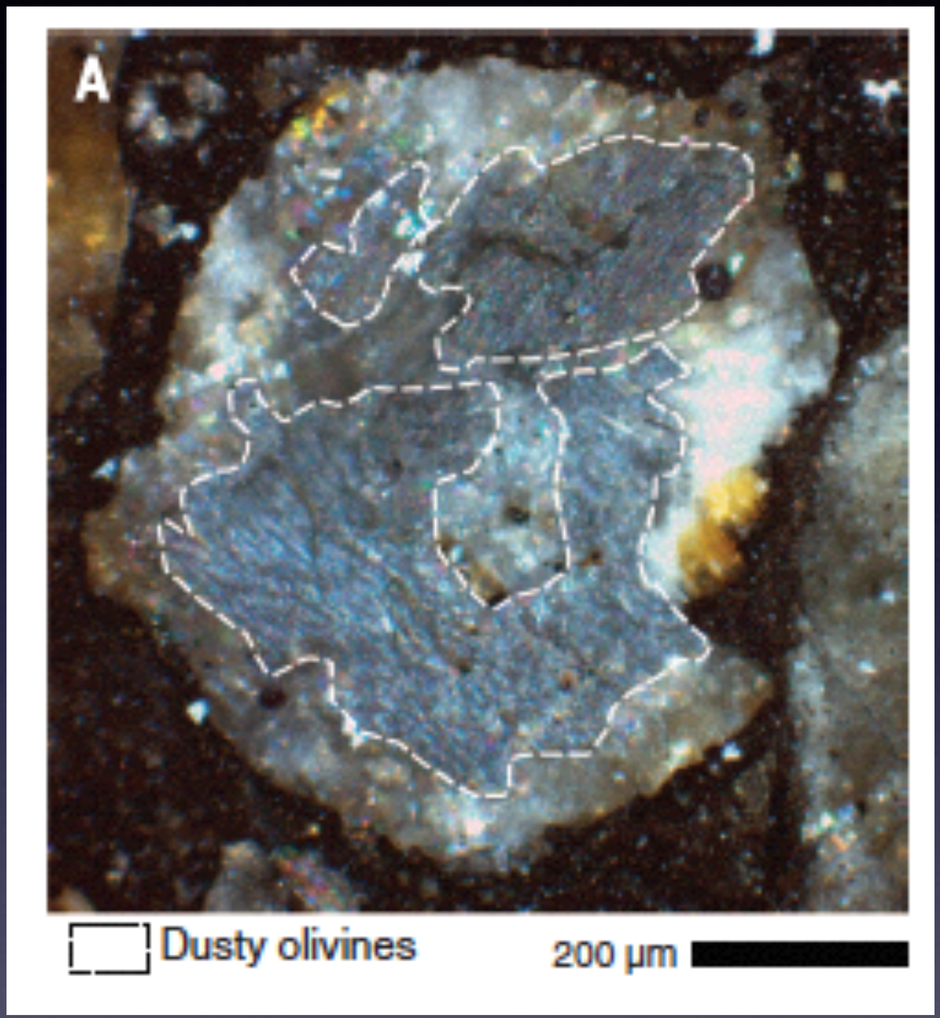
~1mm sized spherical particles formed as molten droplets of silicate (T ~ 1800K)

the cooling rate is
~ 10 - 1000 K per hour
(the nebular gas is needed)

kept forming for 3-5 Myr after CAI formation began, which is 4.567 Gyr ago

cf) Mars formed at ~2 Myr after CAI formation

New information from lab experiments
: magnetic fields in the nebula (disk)



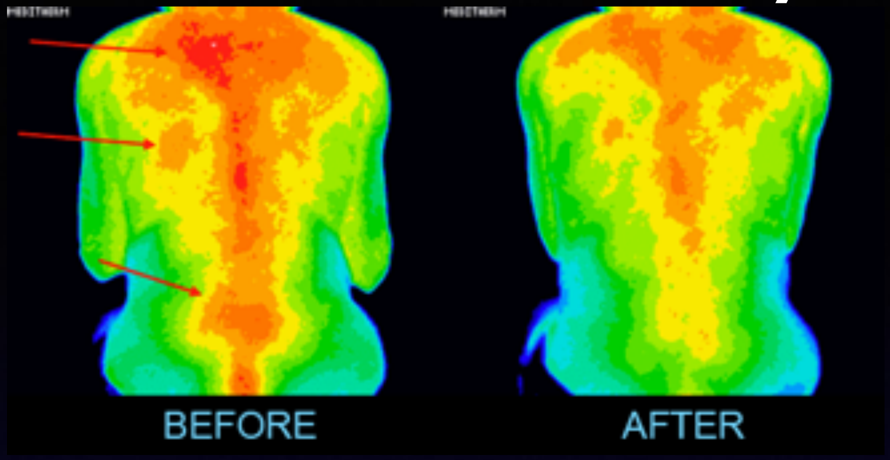
Fu et al 2014

Semarkona meteorite
: primitive, ordinary chondrite

Both thermoremanent magnetization & its direction
=> olivine-bearing chondrules were magnetized in the solar nebula

B-fields in the solar nebula were ~ 50 - 540 mG
=> Level of turbulence in the nebula can be estimated!!

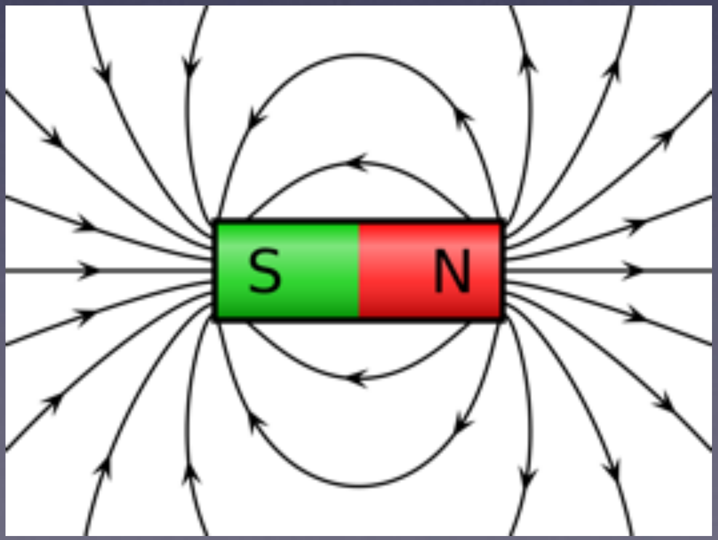
Thermal History



Abundance

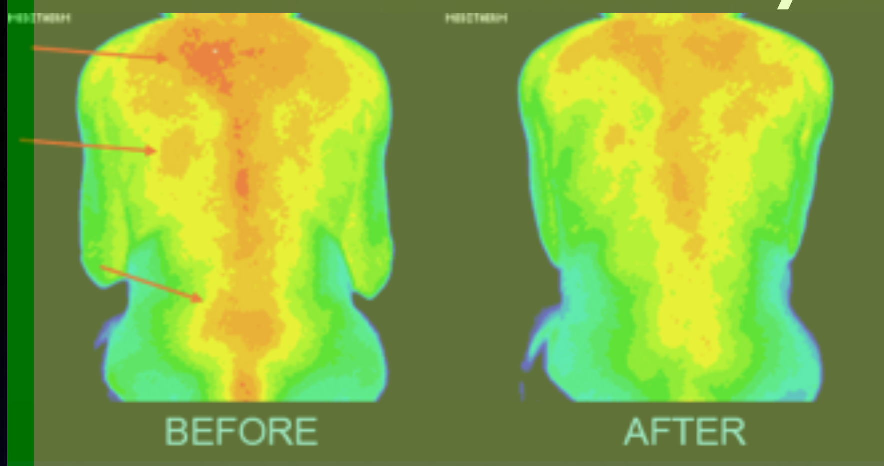
Chondrule Formation
& Accretion

Timescale



B-fields

Thermal History



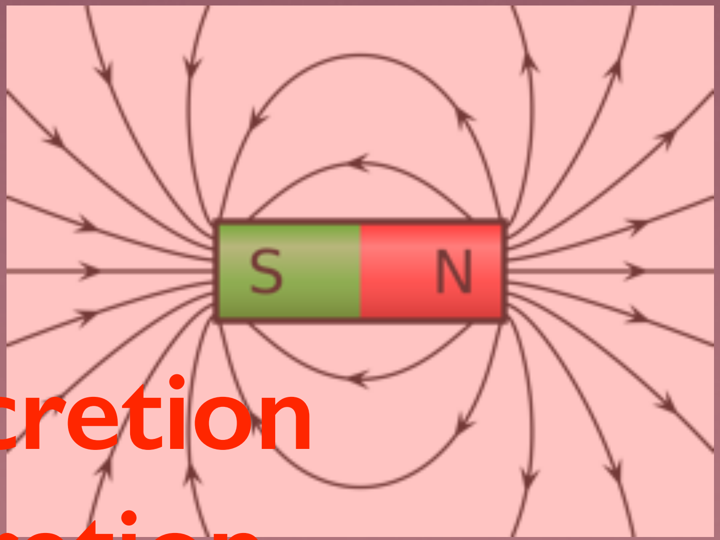
Abundance

Chondrule Formation
& Accretion

Chondrule Formation
= Impact Jetting

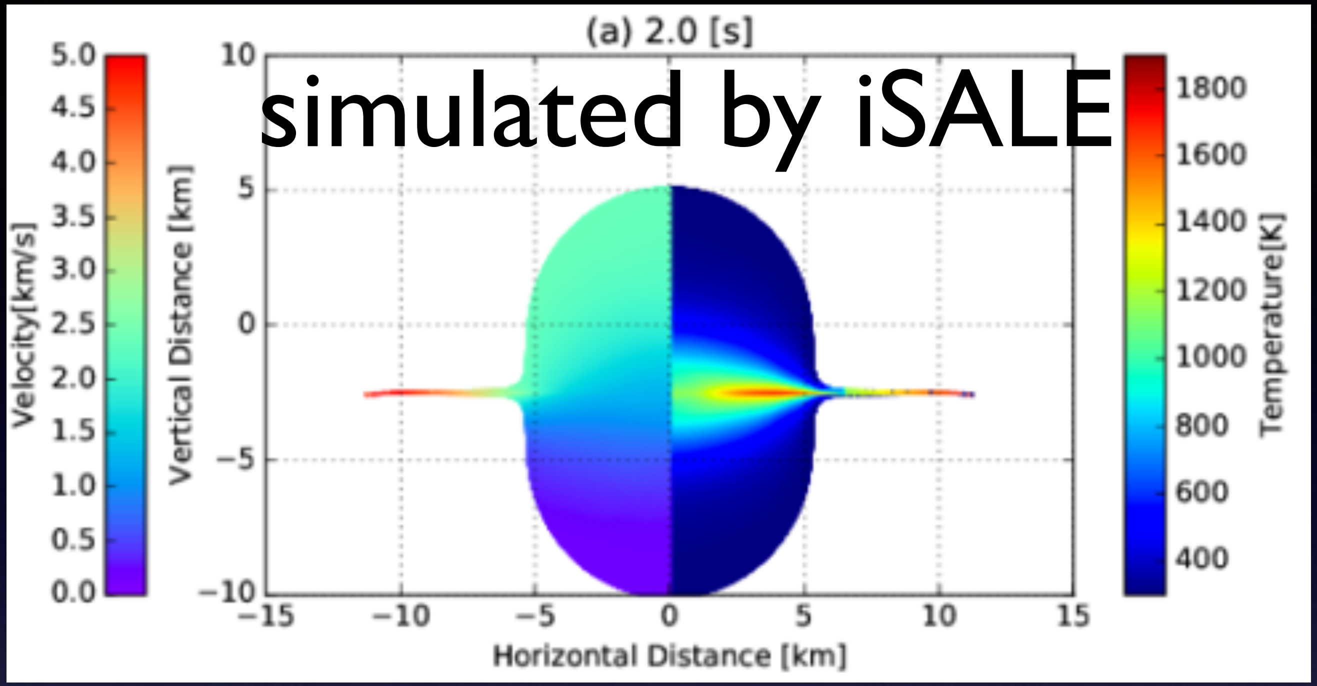
Timescale

Chondrule Accretion
= Pebble Accretion



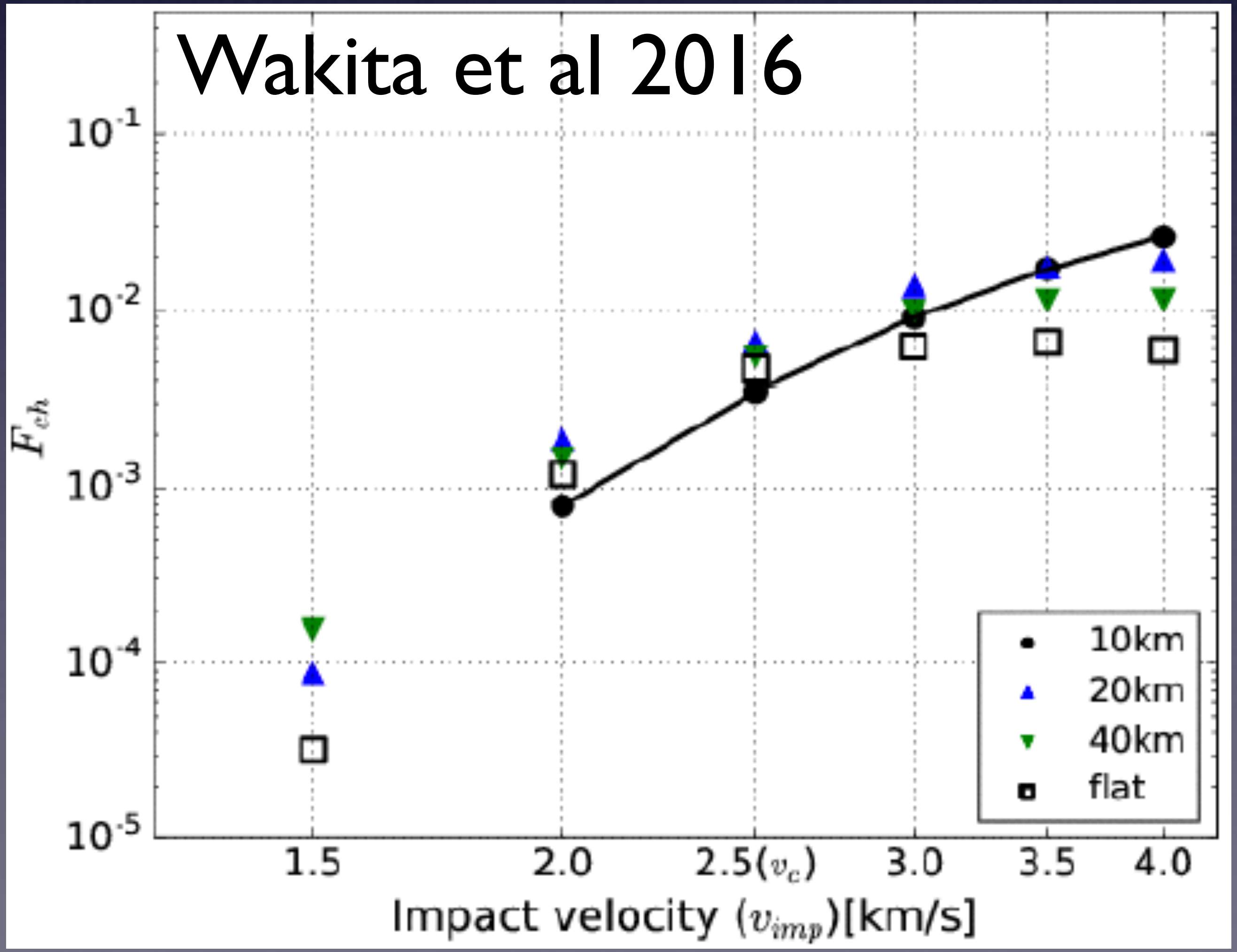
B-fields

Key idea: impact jetting



e.g., Johnson et al 2015

A planetesimal with r = 5km collides with a planetesimal or a protoplanet



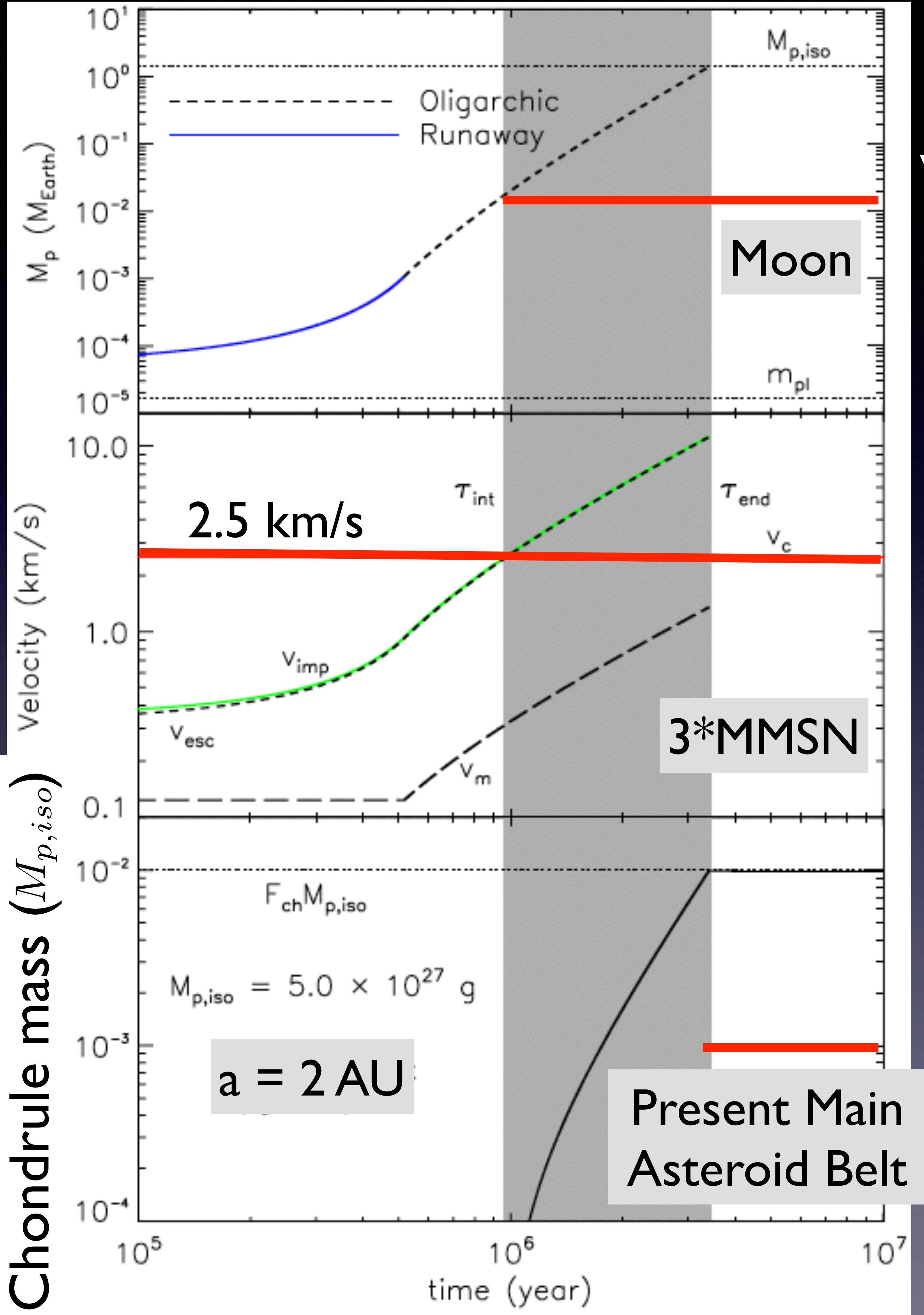
Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

Total ejected mass is about 1% of impactors' mass when v > 2.5 km/s

Lots of collisions occur when protoplanets form

Hasegawa et al 2016a



Protoplanets form via runaway/oligarchic growth

Impact velocity of 2.5 km/s is achieved in the oligarchic pha

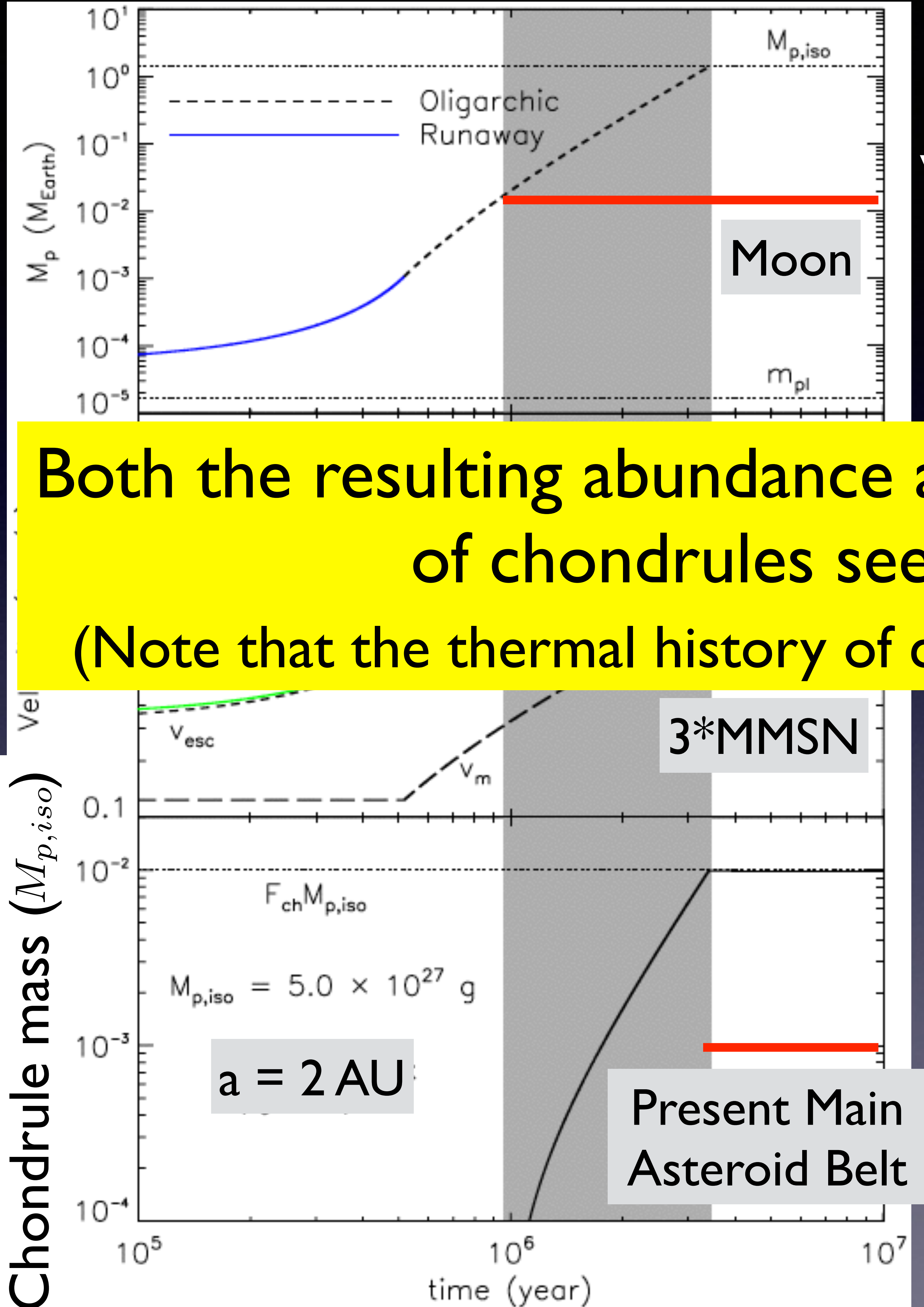
Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN =
the Minimum Mass of the Solar Nebula

Lots of collisions occur when protoplanets form

Hasegawa et al 2016a



Protoplanets form via

Both the resulting abundance and the formation timescale of chondrules seem reasonable!!

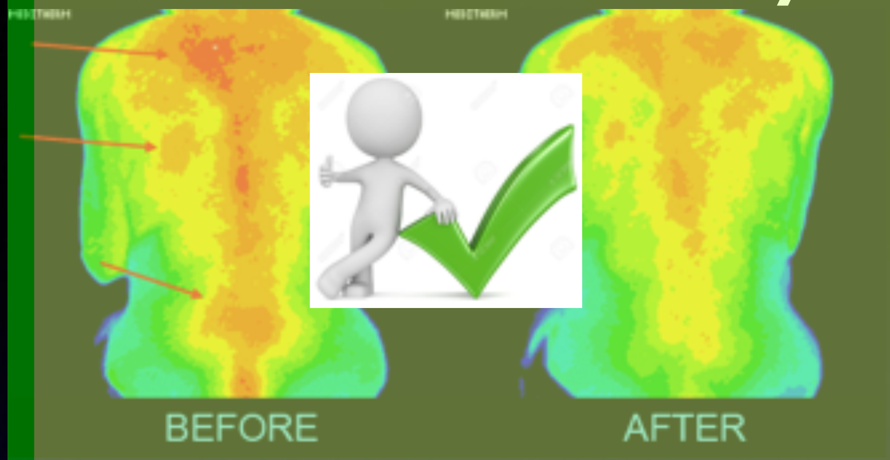
(Note that the thermal history of chondrules is also probably fine)

Chondrule-forming collisions occur at the hatched region

The total chondrule abundance is 1 % of the protoplanet mass

MMSN = the Minimum Mass of the Solar Nebula

Thermal History



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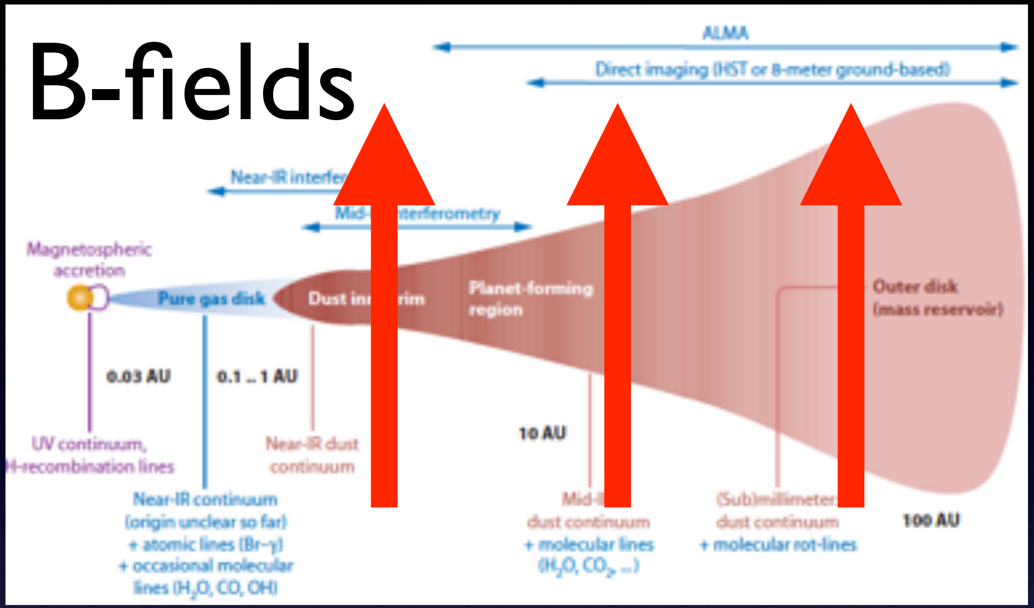
= Pebble Accretion

B-fields

Lab results (magnetic fields) come into play!!!



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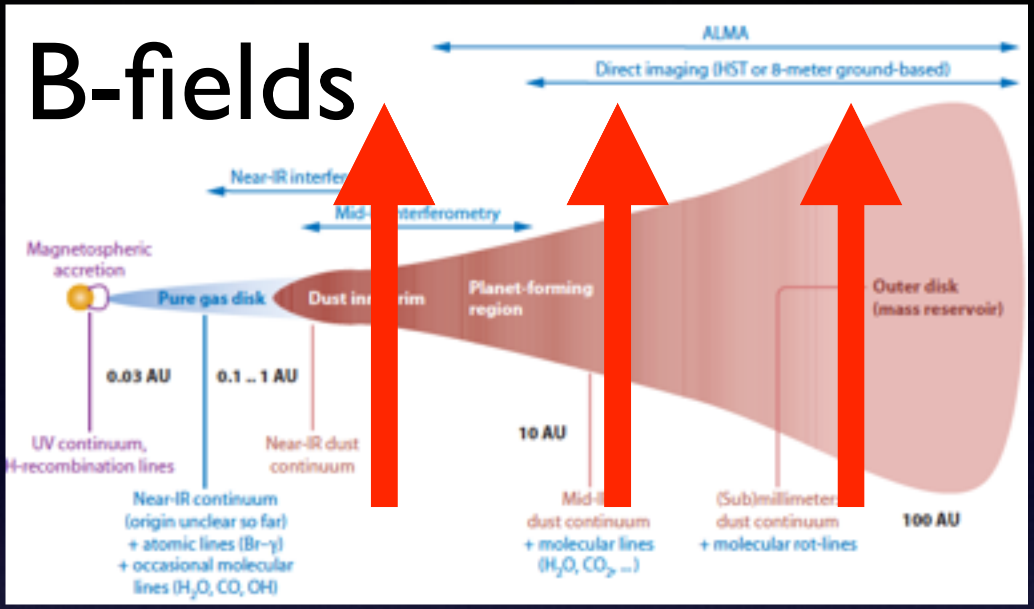
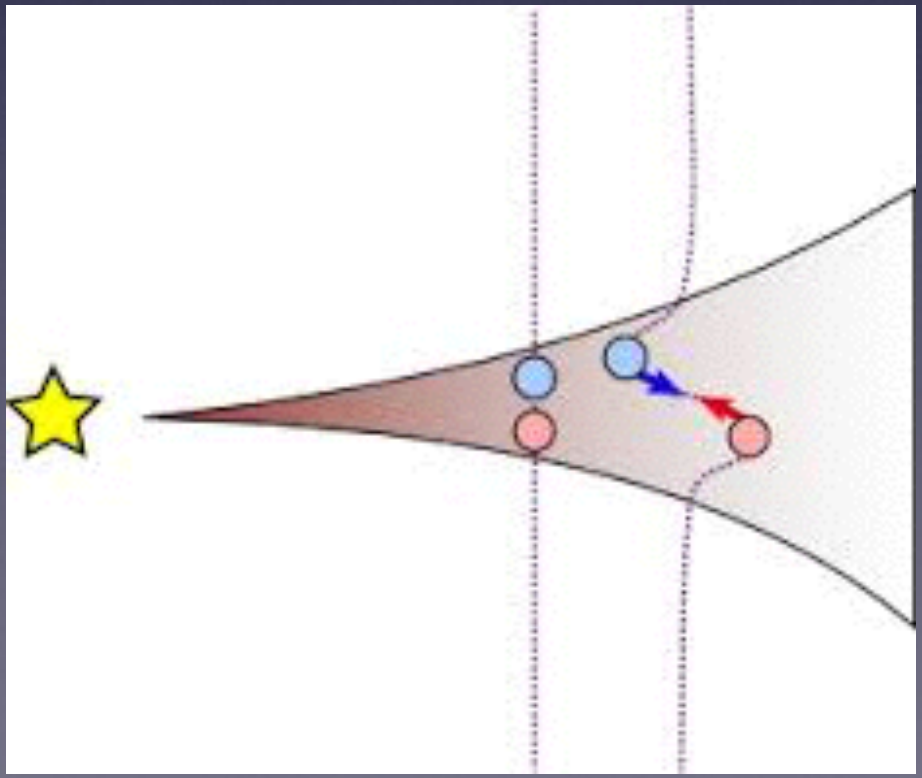
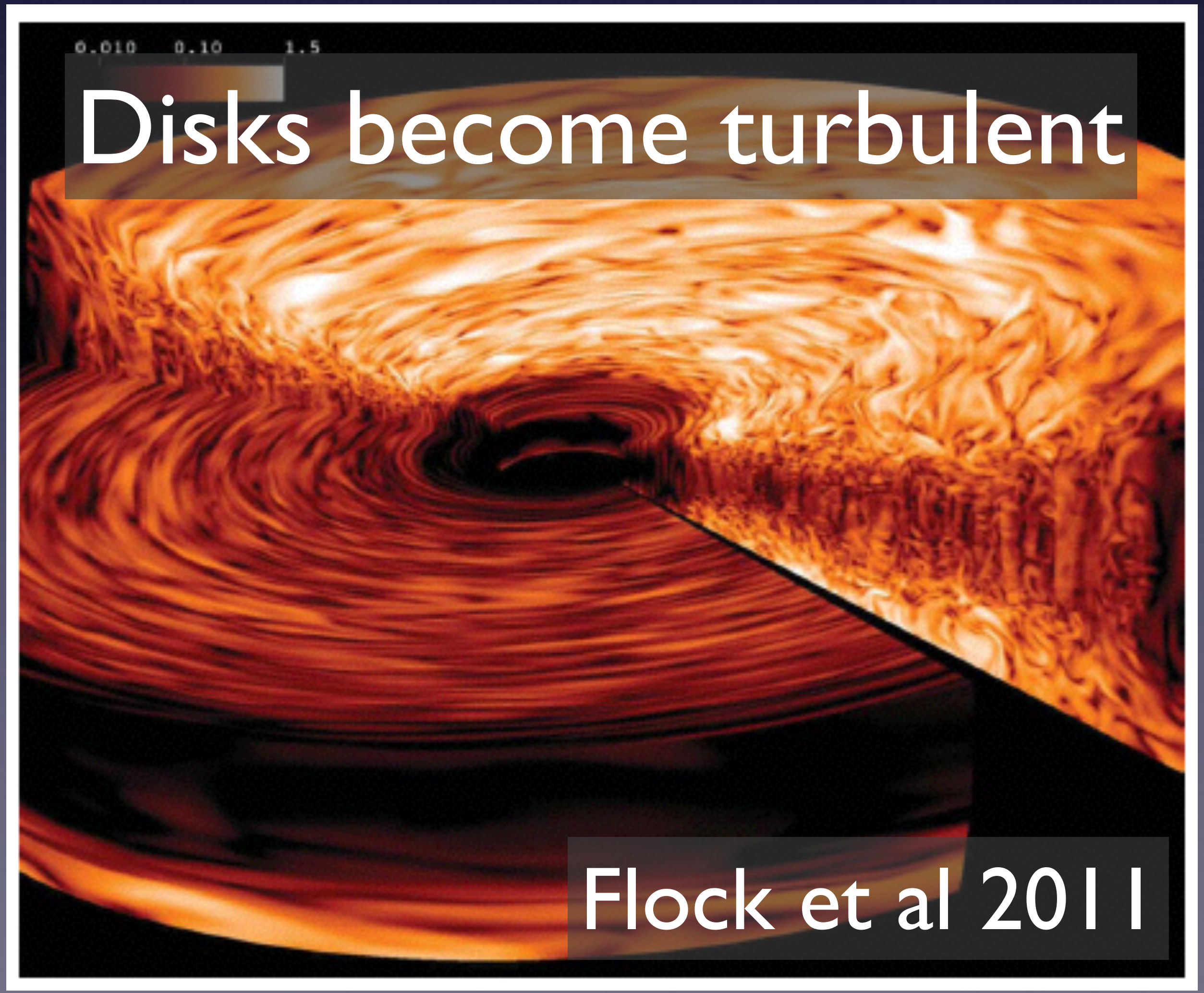


MagnetoRotational Instability (MRI) can operate





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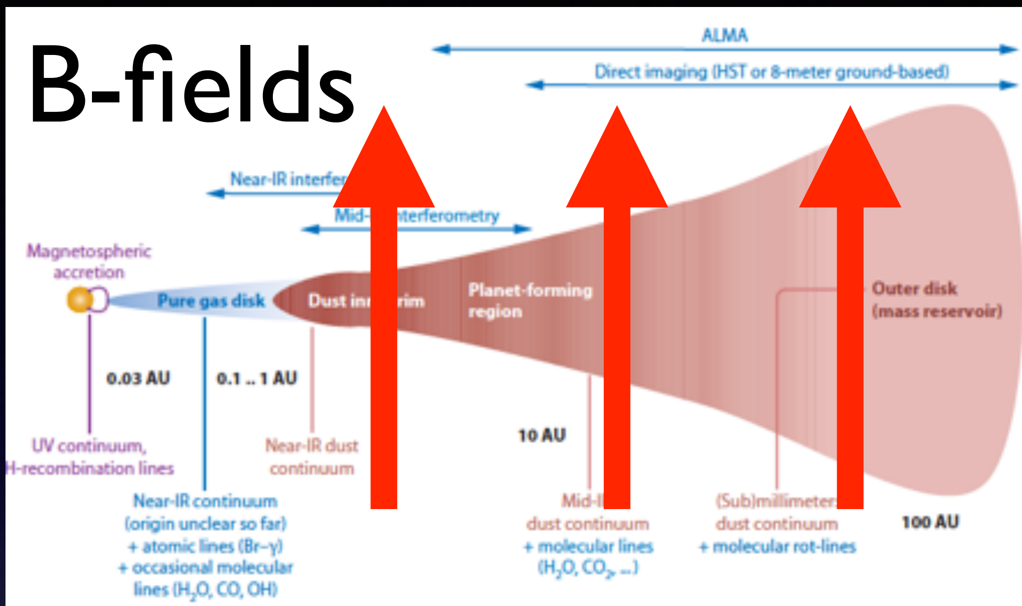
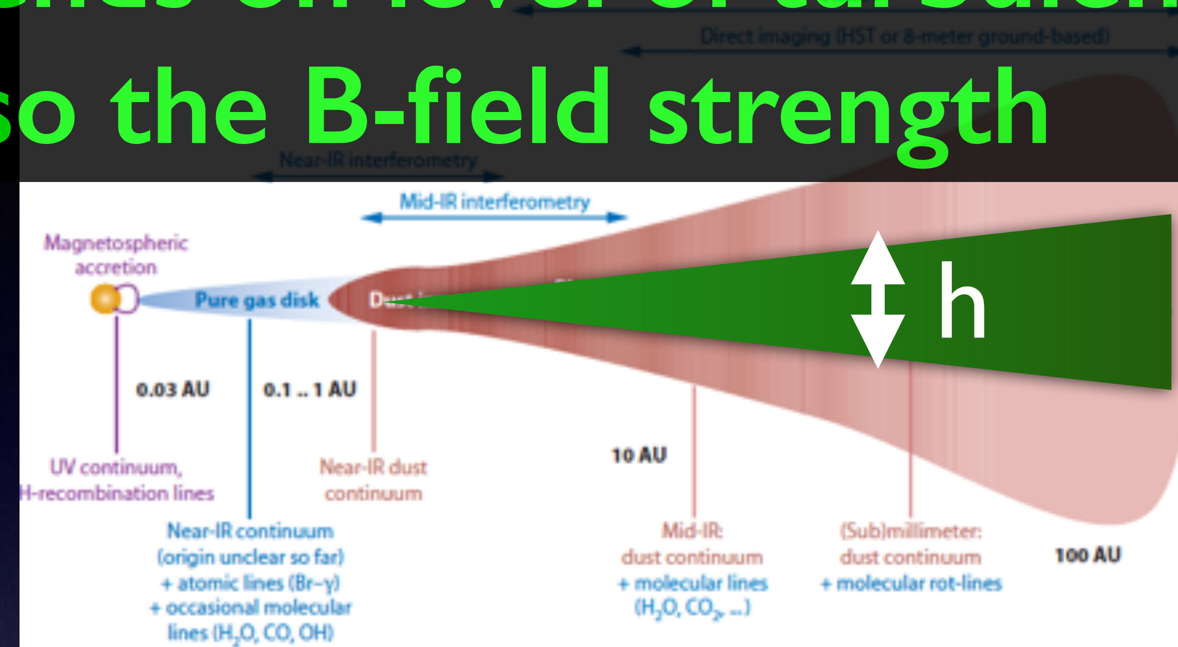


h depends on level of turbulence, so the B-field strength



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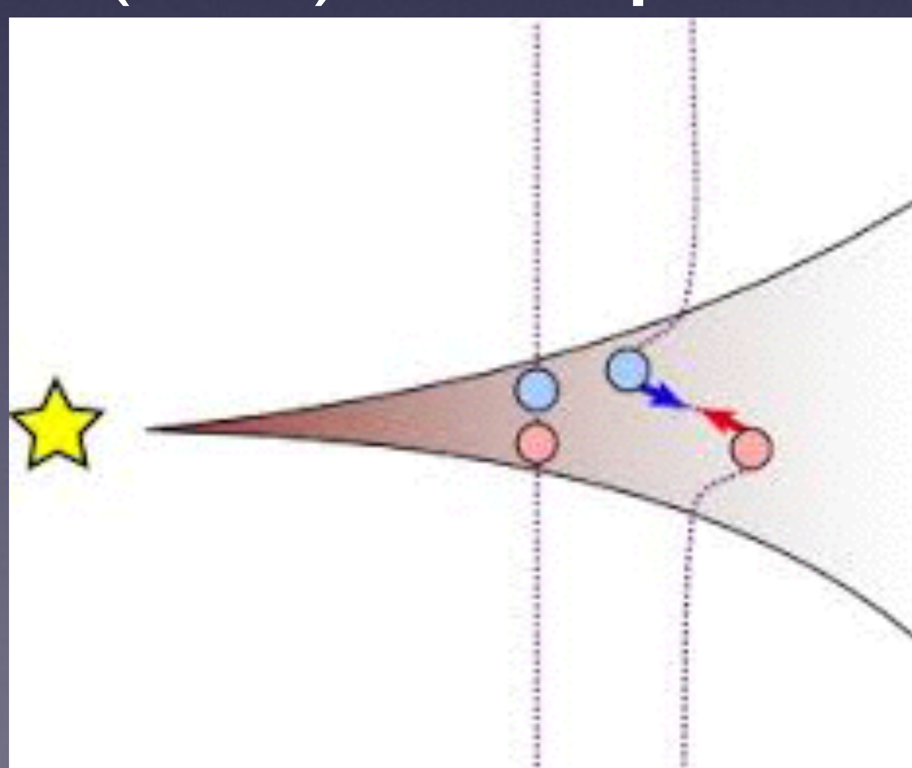
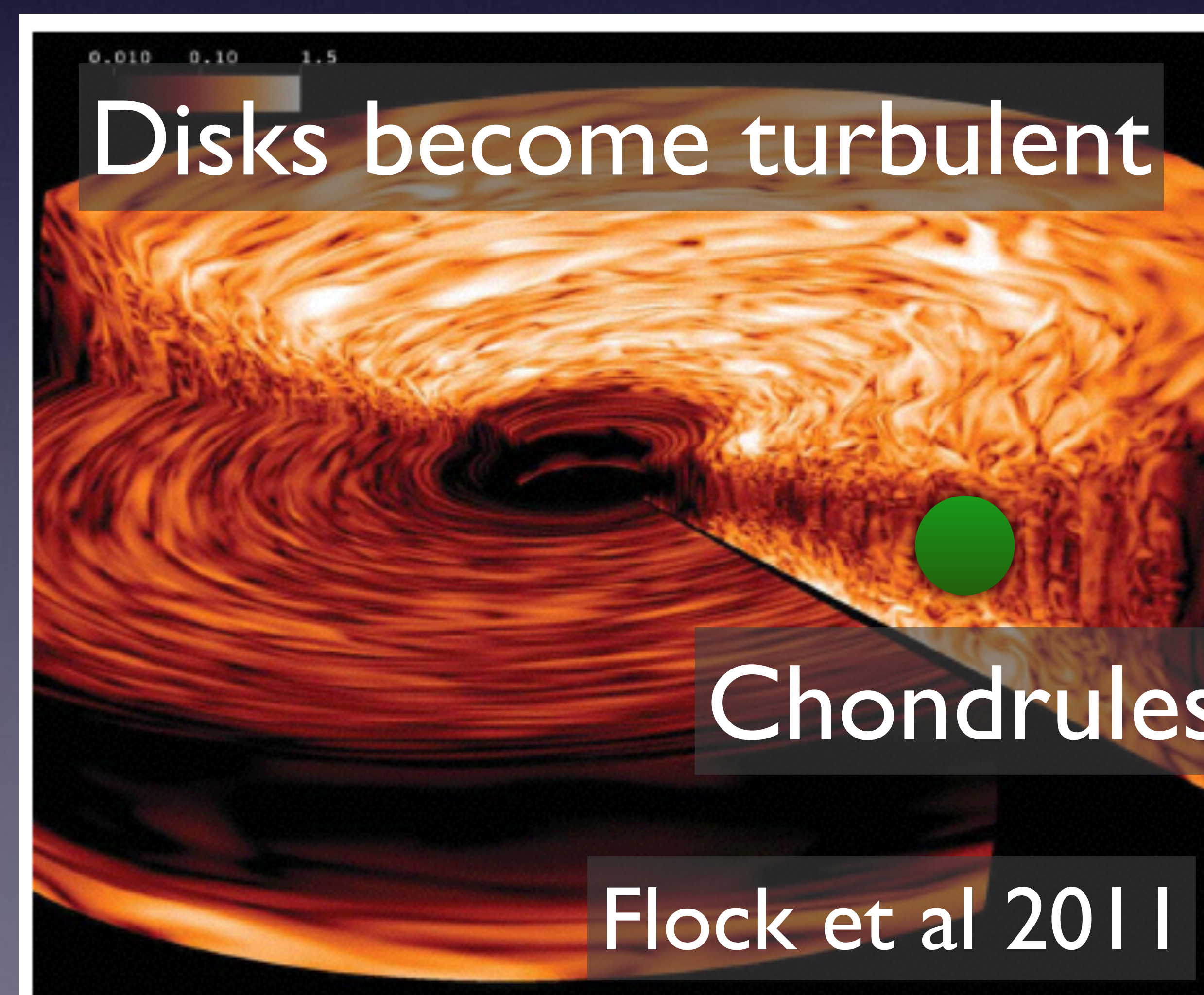
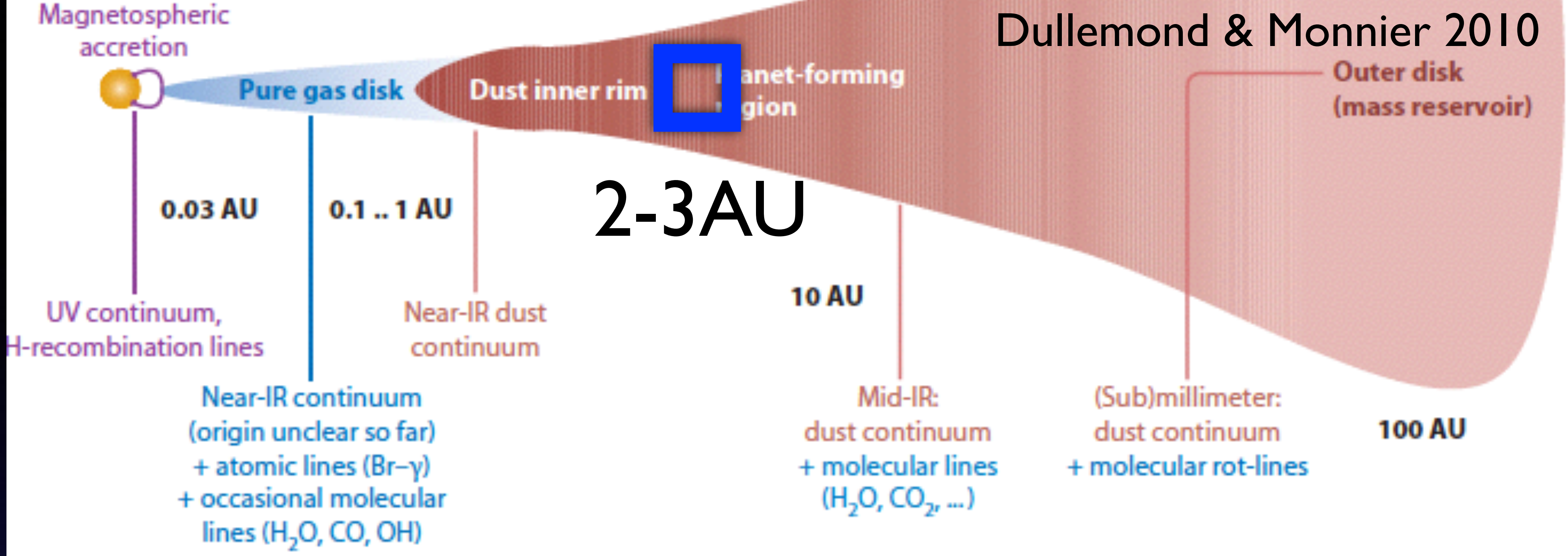
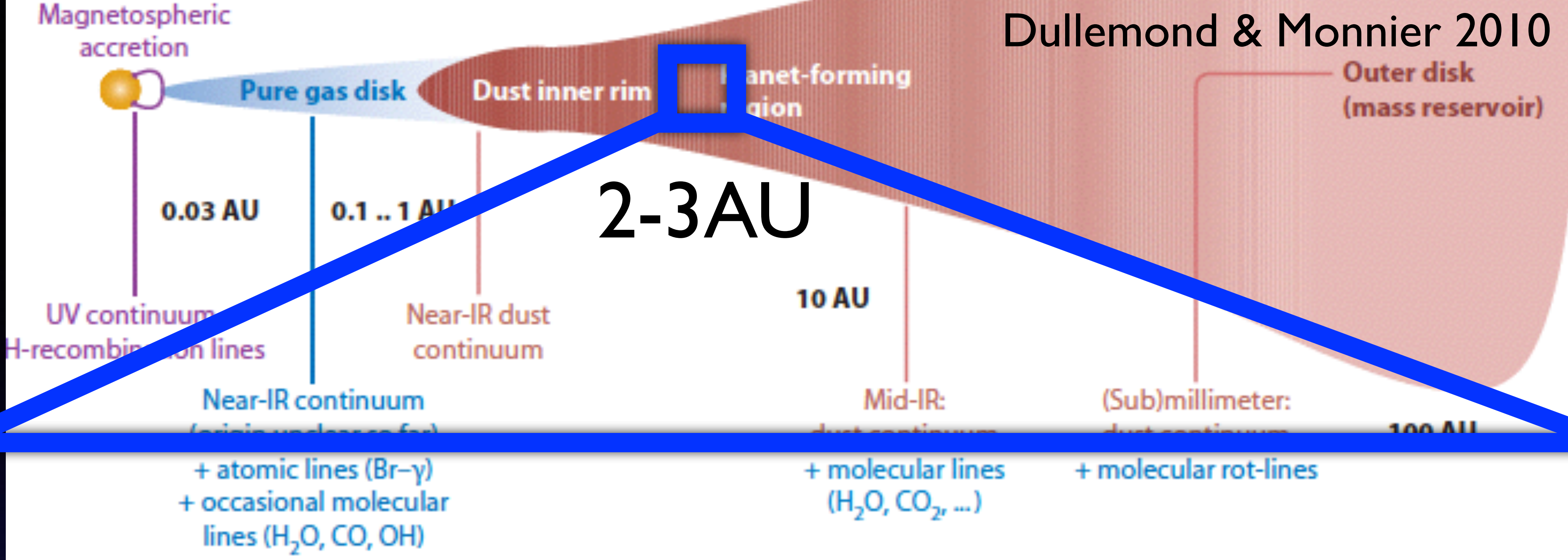


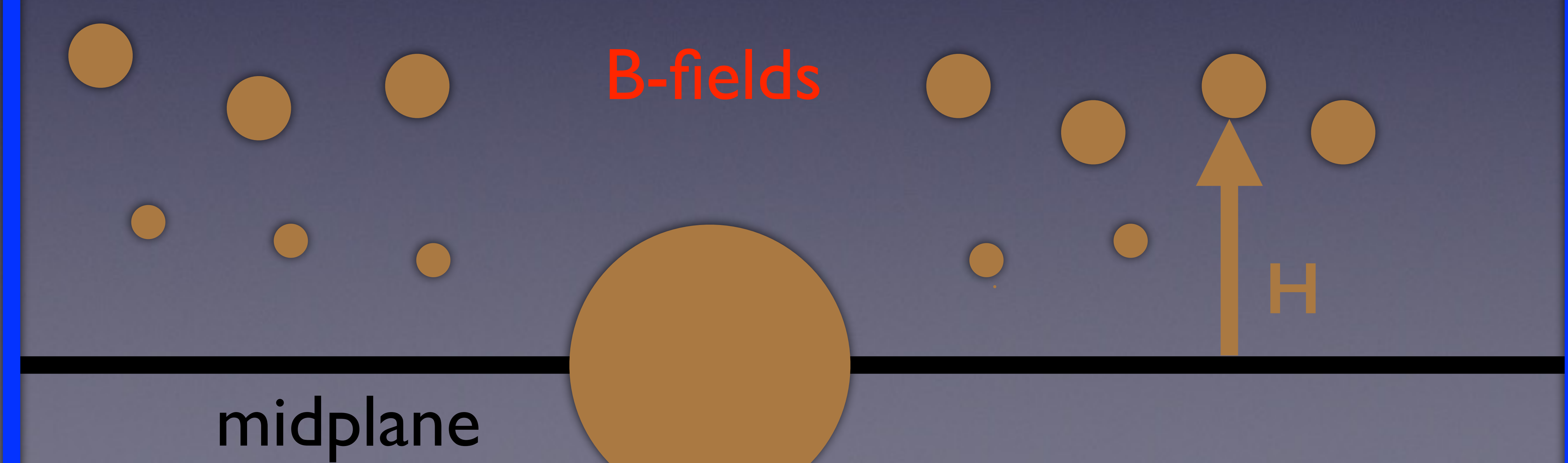


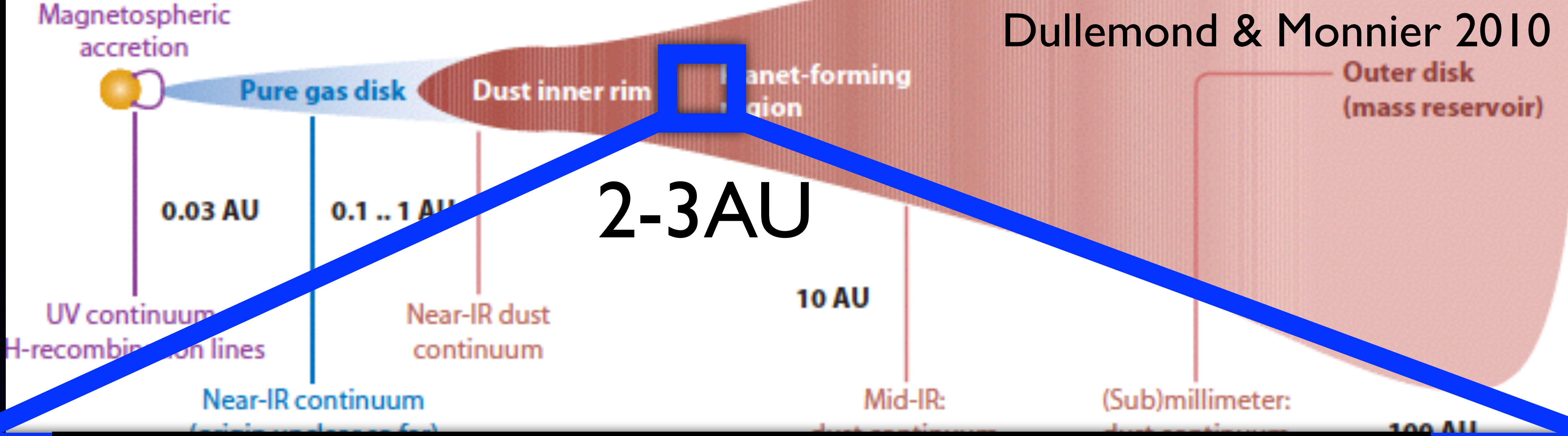

Dullemond & Monnier 2010
Magnetospheric accretion
Pure gas disk
Dust inner rim
anet-forming
gion
Outer disk
(mass reservoir)
2-3AU
0.03 AU
0.1 .. 1 AU
10 AU
100 AU
UV continuum,
H-recombination lines
Near-IR dust
continuum
Near-IR continuum
(origin unclear so far)
+ atomic lines (Br–γ)
+ occasional molecular
lines (H_2O, CO, OH)
Mid-IR:
dust continuum
+ molecular lines
(H_2O, CO_2, ...)
(Sub)millimeter:
dust continuum
+ molecular rot-lines

Dullemond & Monnier 2010



H increases with disk mass and planetesimal mass (protoplanet)



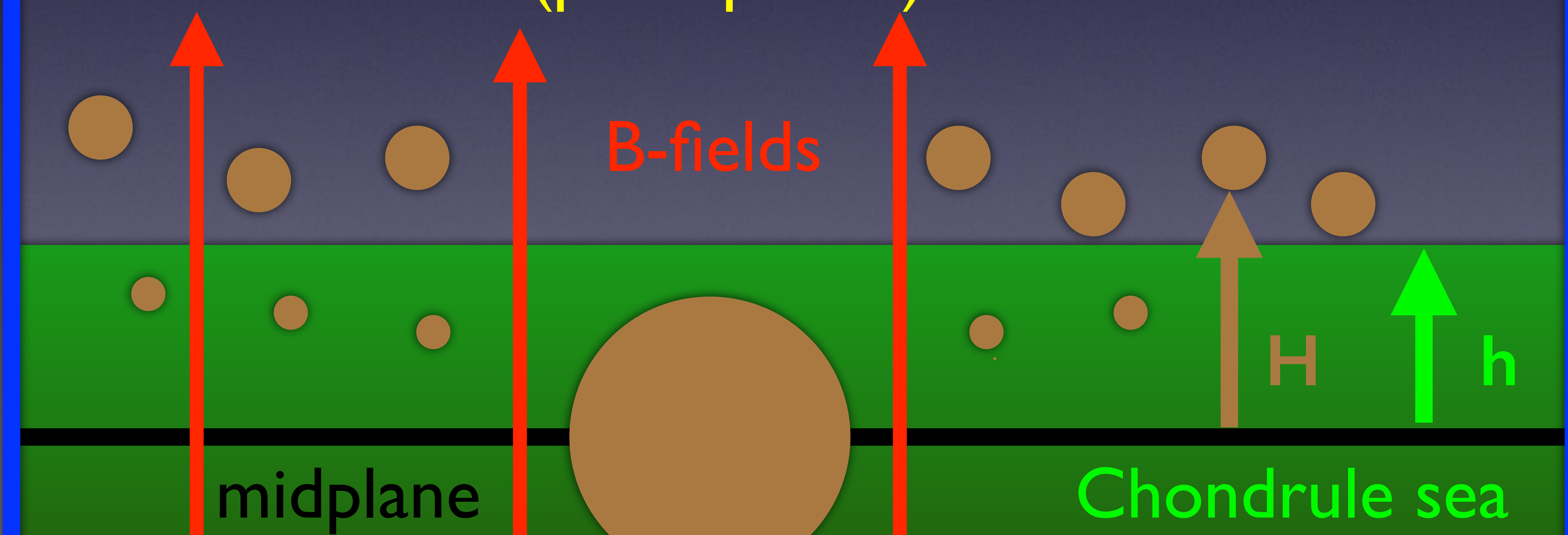


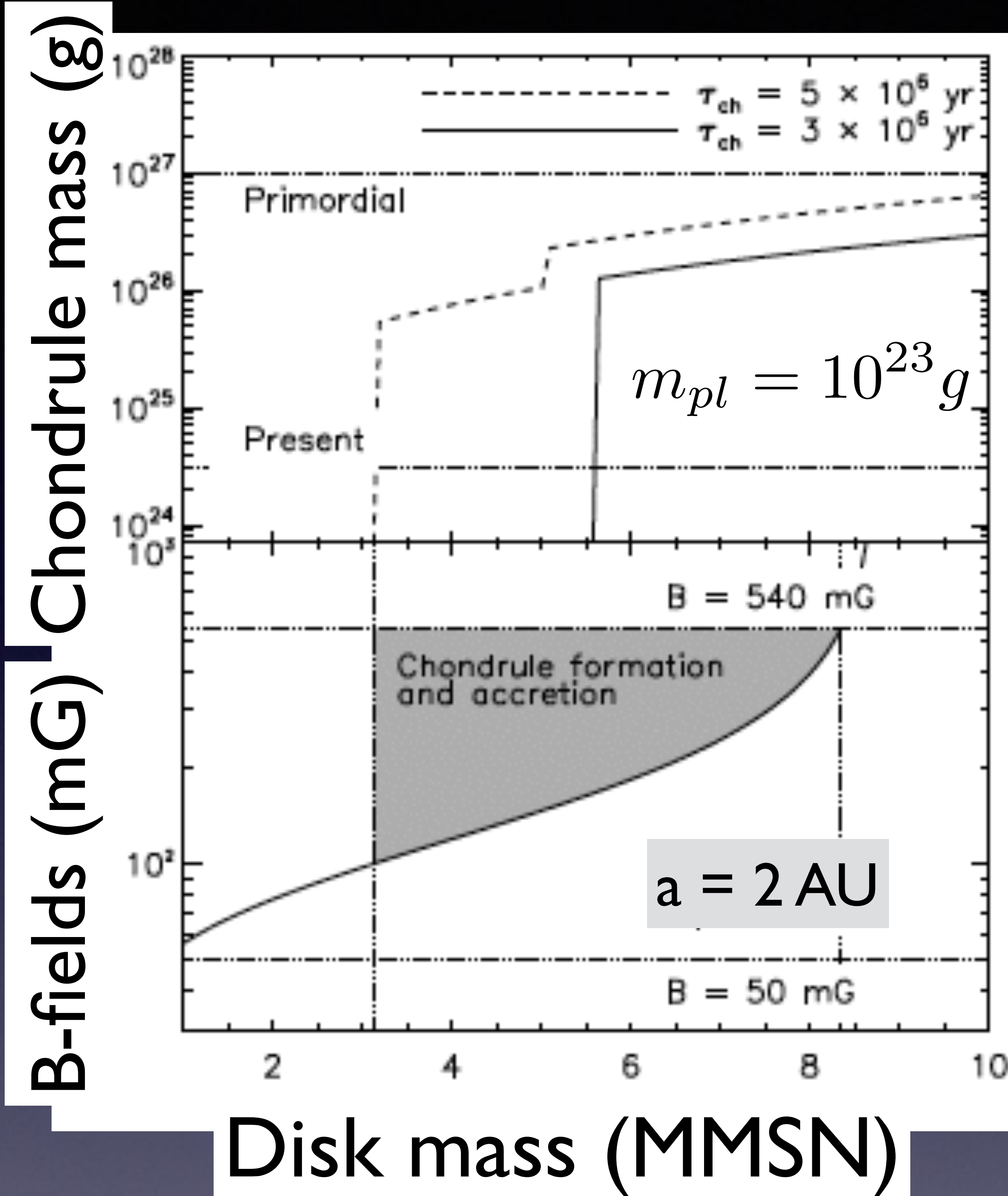
Chondrule accretion onto planetesimals occurs when H < h

Lesion et al 2015

h increases with vertical magnetic flux

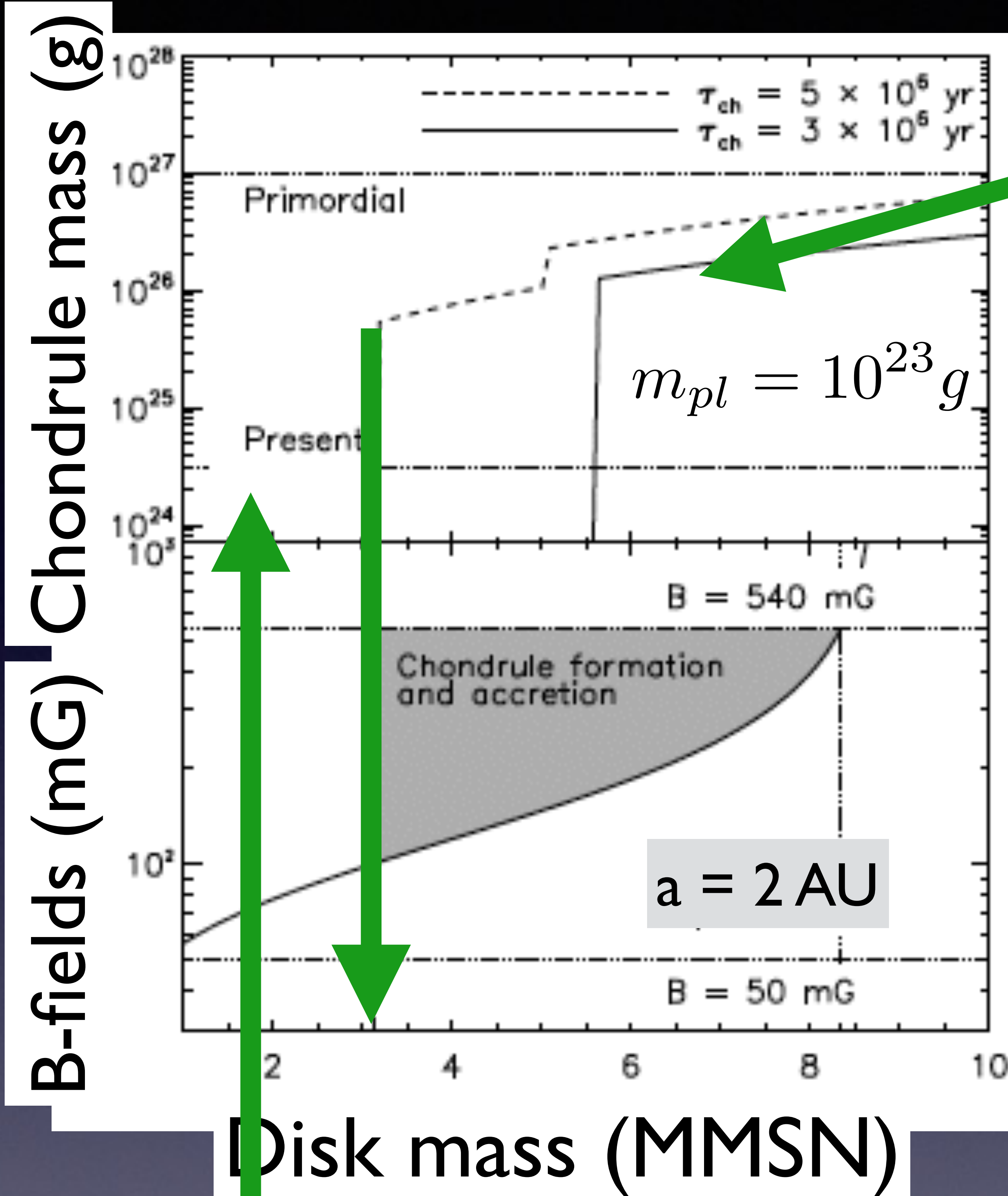
H increases with disk mass and planetesimal mass (protoplanet)





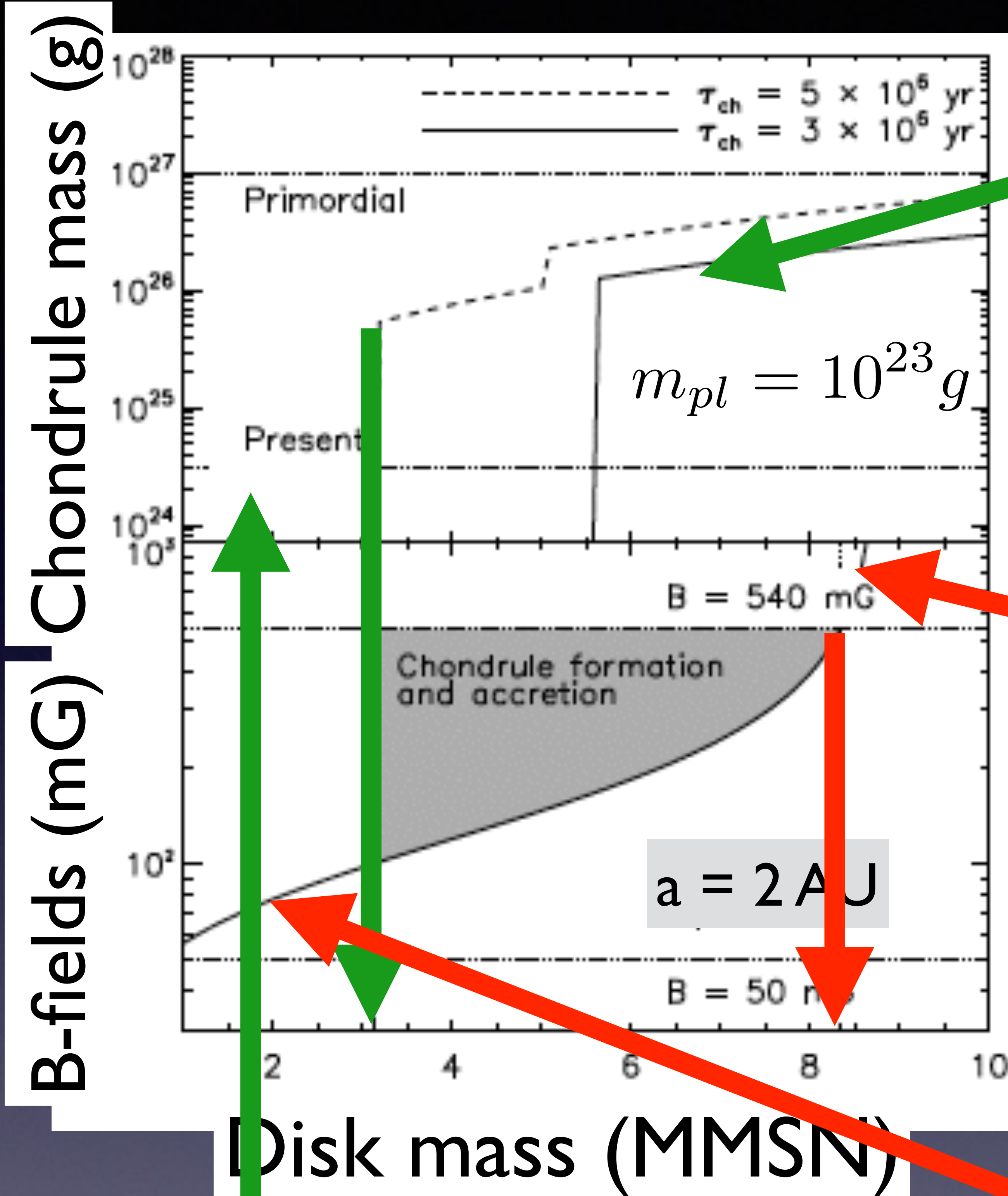
Hasegawa et al 2016b

A large number of chondrules form in massive disks



No chondrule formation due to a low disk mass

Hasegawa et al 2016b



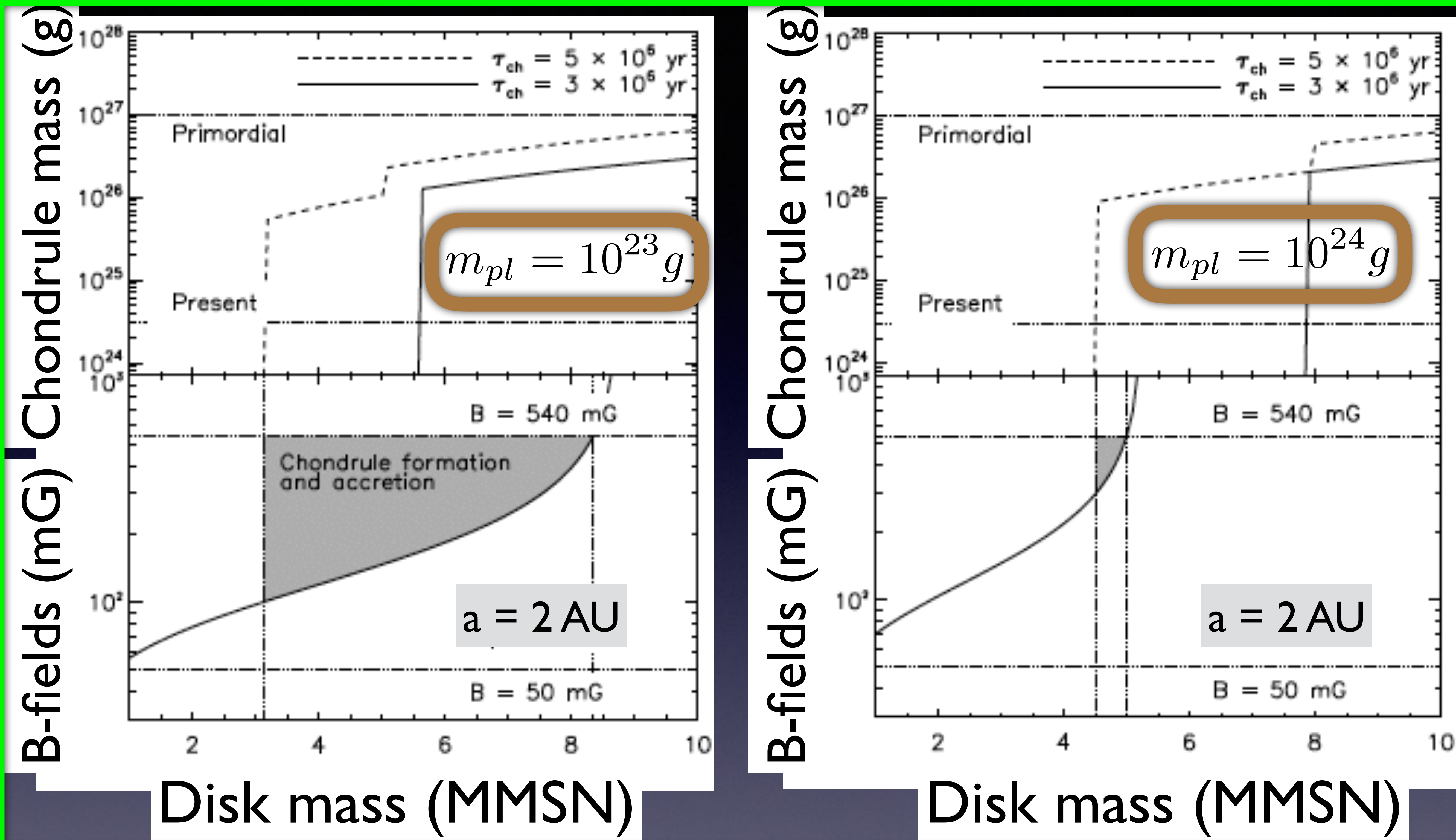
A large number of chondrules form in massive disks

A very strong magnetic field is needed for chondrules to have the same height as planetesimals

Planetesimals can reside in the chondrule sea, but no chondrules indeed

No chondrule formation due to a low disk mass

Hasegawa et al 2016b

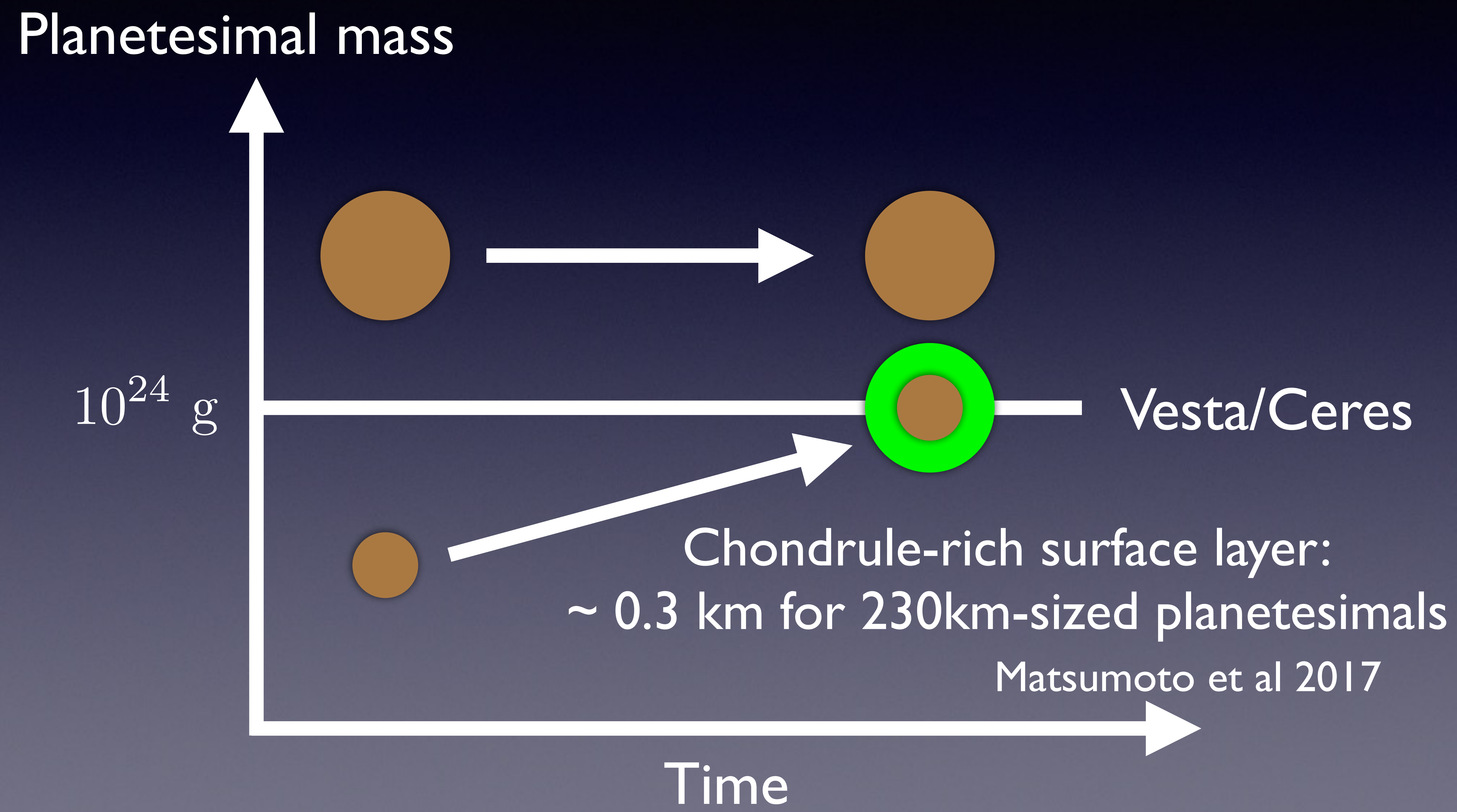


All the currently available meteorite data can be satisfied when the disk mass is < 5 MMSN the planetesimal mass is < 10^{24} g

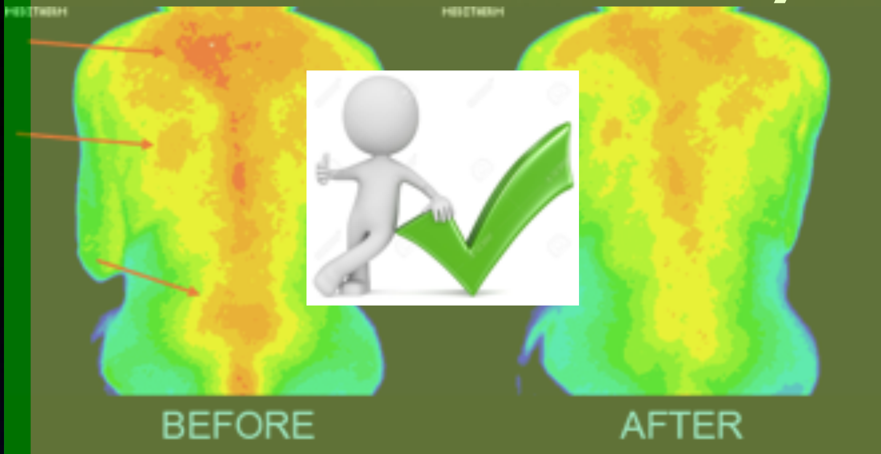
Hasegawa et al 2016b

Our model needs a first generation of planetesimals that trigger impact jetting and serve as parent bodies to accrete chondrules

Hasegawa et al 2016b



Thermal History



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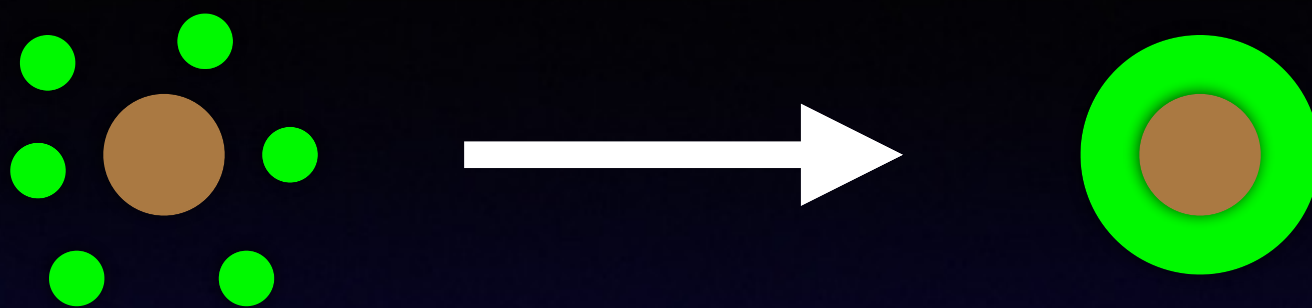
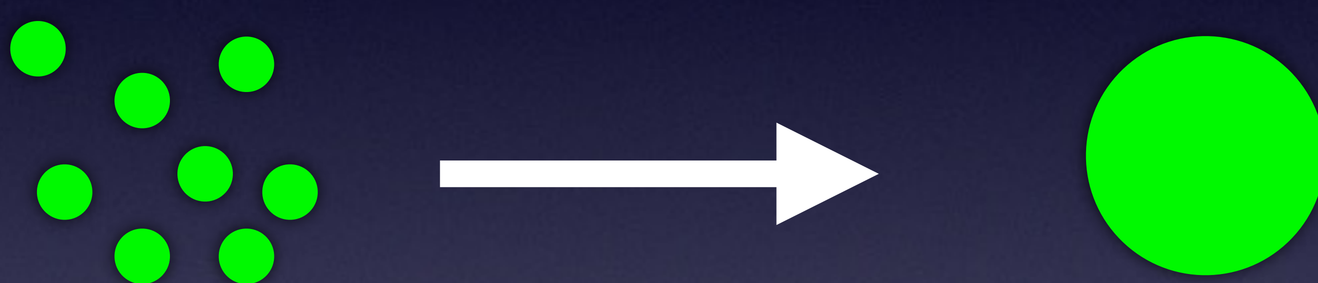
B-fields

Planetesimal Formation & Origins of Asteroids

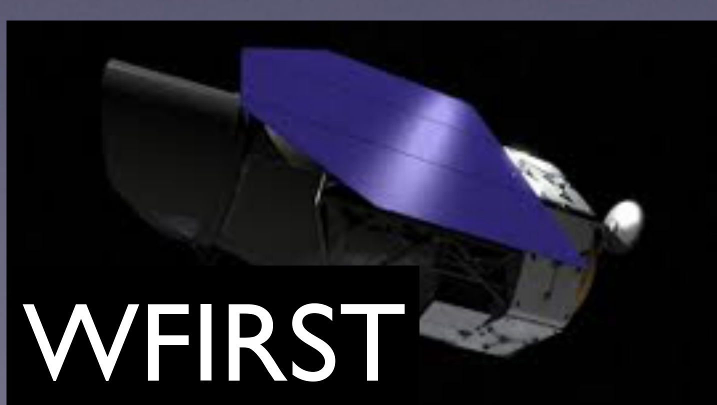
Scenario 1: Chondrule accretion



Scenario 2: Chondrule accumulation



We will identify formation mechanism(s) of planetesimals



Applications to exoplanetary systems: debris disks

Summary

Hasegawa et al 2016a, ApJ, 816, 9
Hasegawa et al 2016b, ApJ, 820, L12
Wakita et al 2017, ApJ, 834, 125
Matsumoto et al 2017, ApJ, 837, 103

- Primitive meteorites contain fossil records of the solar system
- Coupling of impact jetting with subsequent chondrule accretion is a promising scenario to account for the currently available meteorite data
- all the requirements can be met when the disk mass is < about 5 MMSN and the planetesimal mass is < about 10^{24} g
- Our model implies that only primordial asteroids that were originally smaller than 500 km in radius may have a chondrule-rich surface layer (~ 0.3 km)!!
- The upper limit of the planetesimal mass is comparable to that of Vesta/Ceres, and current observations/missions may provide an invaluable opportunity to verify our scenario!!